

Direct Arterial Pressure Monitoring

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Direct arterial pressure monitoring is a common practice in the modern intensive care unit and during complex anaesthesia cases. The methods for catheter introduction and maintenance are widely described and used. However, in the past few years there have been new developments and controversies surrounding direct arterial pressure measurement. First, rugged, inexpensive and convenient disposable transducers are supplanting the former expensive, fragile reusable transducers. Second, the fidelity or dynamic response required to reproduce the 'real' arterial pressure waveform continues to be a subject of controversy and concern. This review attempts to clarify the dynamic response issues and show how to test pressure monitoring systems in the clinical setting. Third, the arterial pressure waveform is distorted as it is transmitted from the aorta to peripheral arteries. Fourth, computer processing of the arterial waveform that presents 'digital' results must be improved. In some situations, the digitally displayed numbers 'lie'. Despite the issues noted the use of direct arterial pressure measurement is a convenient, safe, and helpful method for continuously monitoring patients.

Stephen Hales, a versatile English theologian-scientist, made the first measurement of direct arterial blood pressure with a water manometer in a horse in 1773.¹ Since that time much has happened to the measurement of direct blood pressure. In the USA alone, more than eight million arterial catheters are inserted each year. These catheters are used to measure blood pressure and as a site for withdrawal of samples for blood gas analysis. The direct or invasive measurement of blood pressure allows for continuous and accurate assessment of blood pressure. Continuous pressure measurement allows for the detection of dangerous haemodynamic events and provides information necessary to initiate and titrate patient therapy. Notwithstanding its common use

and worth, direct arterial pressure monitoring only provides valuable information when it is obtained accurately.

The most important steps in getting accurate arterial blood pressure data are to understand the measurement principles, use simple set-up procedures and establish standardized procedures. From my years of experience with blood pressure monitoring, it is clear that large measurement errors occur. Because invasive direct arterial pressure monitoring involves substantial cost, risk of infection, and other complications, one must be concerned with the necessity and benefit of invasive monitoring. On the other hand, carefully established invasive monitoring techniques can minimize the risk to the patient and maximize the accuracy of the data being measured. For the foreseeable future, a large number of critically ill patients and those undergoing complex anaesthesia will require direct arterial pressure

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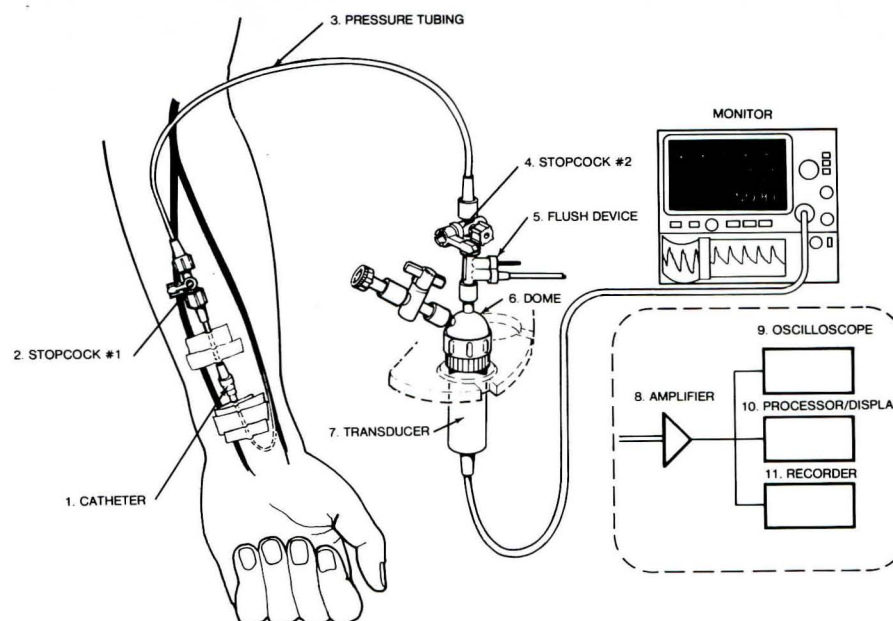


Fig. 1 — The 11 components used to monitoring direct arterial blood pressure. The size of the transducer and the plumbing components are enlarged for illustration purposes. (Reproduced with kind permission from reference 2)

measurements. This review attempts to update users on the developments and controversies of the past few years.

Equipment used for direct pressure measurement

Figure 1 shows all the components of an invasive blood pressure monitoring system.²⁻⁸ The components labeled 1–7 in Figure 1 are commonly known as the 'plumbing system', and must always be sterile because they come in direct contact with the patient's blood. Usually these components are disposable and are often discarded after 2 or 3 days to minimize the risk of infection. The other components (8–11) in the system are used for processing and displaying pressure waveforms and presenting 'digital' blood pressure values. The function and problems associated with some of these elements have been discussed in earlier literature.

Direct arterial pressure monitoring requires a detailed knowledge of equipment set-up and troubleshooting. Table 1 outlines problems frequently encountered when monitoring pressures, lists potential causes and suggests preventive measures or interventions to solve the problems.⁹ Besides this troubleshooting guide there are several areas of direct pressure monitoring that warrant further discussion.

The accuracy of blood pressure readings depend on establishing an accurate reference point from which all subsequent measurements are made. The patient's mid-axillary line (right heart level) is the reference point most commonly used. The zeroing process is used to compensate for offset caused by hydrostatic pressure differences, or offset in the pressure transducer, amplifier, oscilloscope, recorder, or display.

Zeroing is accomplished by opening an appropriate stopcock to atmospheric pressure and aligning the resulting fluid-air interface with the mid-axillary reference point. Figure 2 shows two methods that can be used to zero a pressure monitoring system.

In the past few years there have been new device developments and controversies generated related to invasive pressure monitoring. Four such topics deserve further attention.

Disposable pressure transducers

Pressure transducers are available in a variety of shapes and sizes. Most pressure transducers today are resistive bridge devices that convert the movement of their sensing diaphragm into an electrical signal. Recently standards for blood pressure transducers have been developed by the Association for the Advancement of Medical Instrumentation (AAMI) and adopted by the American National Standards Institute (ANSI).¹⁰ These standards have greatly simplified transducer selection and now allow the same transducer to be used interchangeably with any bedside monitor. Several excellent quality disposable pressure transducers are now available^{9,10} – also see Figure 3. They are smaller, technically superior, and can better withstand the rigors of clinical use than the outdated reusable transducers. Since they are a single use device the difficulties of cleaning and sterilizing are eliminated. In the USA it is more cost effective to pay for and use disposable transducers than to clean and repair the multiple use transducers or employ disposable diaphragm domes with their attendant problems.^{9,10,11}

Seventy-five percent (or about 8 million) of the approximately 11 million invasive pressures meas-

Table 1 — Troubleshooting Guide for Arterial Monitoring Systems (Reproduced with kind permission from reference 9)

Problem	Cause	Prevention/Intervention
Blood backup in: catheter transducer flush device	Disconnection or leak in pressure system Low pressure (<300 mm Hg) in pressure bag	Return stopcock to proper position Check connections frequently for tightness and leaks Keep pressure bag inflated and flush solution replenished
Air bubbles in: catheter transducer device	Inadequate set-up of pressurized flush system Improper position of stopcocks Leaks or cracks in catheter or flush system	Careful set-up of continuous flush system (CFS) to avoid micro-bubbles Remove bubbles through stopcock if flush possible by placing the opening in a superior position and 'tapping' the flush device so that air bubbles escape out the open stopcock port If there is a stopcock on the transducer dome, simply open the one-way stopcock on the side port and flush fluid and bubbles out of the system Transducers without side ports may require sterile disassembly to remove air bubbles
Pressure stays >200 mmHg when fast flush released	Broken flush device	Replace flush device
'Pegging' on the top of oscilloscope	Clot on catheter tip or tip against vessel wall (occlusion at tip)	Withdraw catheter 1-2 cm Irrigate catheter
Pressure <200 mmHg when fast flush	Not enough pressure or fluid in flush bag	Check for adequate pressure and solution in flush bag
Cannot aspirate blood	Catheter against vessel wall Clot in catheter or at tip	Aspirate clot if possible Do not force flush catheter If catheter irrigates easily, flush with syringe Withdraw catheter 1-2 cm Maintain continuous flush with heparinized solution Look at catheter for kinks
Cannot irrigate catheter	Catheter clotted or kinked Stopcock turned incorrectly	Check catheter for kinks Check position of stopcocks If catheter clotted, replace Do not force flush clotted catheter, aspirate clot if possible
Tracing off top scale of oscilloscope	Stopcock mispositioned Catheter clotted Wrong scale on monitor Improper zero of monitor	Check stopcock position (See above) Change scale on monitor Check monitor zero
Cannot zero	Wrong monitor channel Bad pressure transducer Bad monitor Improper stopcock position	Select proper monitor channel Replace transducer Replace monitor Check position of stopcocks
No waveform on monitor or strip recorder	Transducer not connected to catheter Monitor off, bad zero Catheter clotted Faulty transducer	Check monitor & stopcock position Turn on & check monitor Aspirate clot from catheter Check & replace transducer
Damp dressings around connects or catheter insertion site	Loose connections Cracked connections Worn connections Infiltration of fluid from vessel or site	Check plumbing connections Check catheter hub & catheter Check insertion site
Questionable low or high pressure reading	Improper zero Change in transducer position	Rezero and check transducer position (Hydrostatic) Check transducer calibration
Decreased or absent distal pulse or Extremity cool and discoloured	Thrombosis of artery	Check distal circulation frequently Remove catheter immediately Embolectomy if necessary
Bleeding at insertion site	Coagulation problems Blood leak around catheter	Apply pressure at insertion site Apply pressure dressing or sandbag insertion site
Poor dynamic response	See Table 2	See Table 2

Definitions of terms used in table

Flush device = continuous flush device

Bag = pressurized solution bag which provides flush solution for continuous flush device

CFS = continuous flush system including the flush device and bag

Damped = waveform which is smoothed off and not sharp feature

Line = catheter and attached plumbing system for monitoring pressure

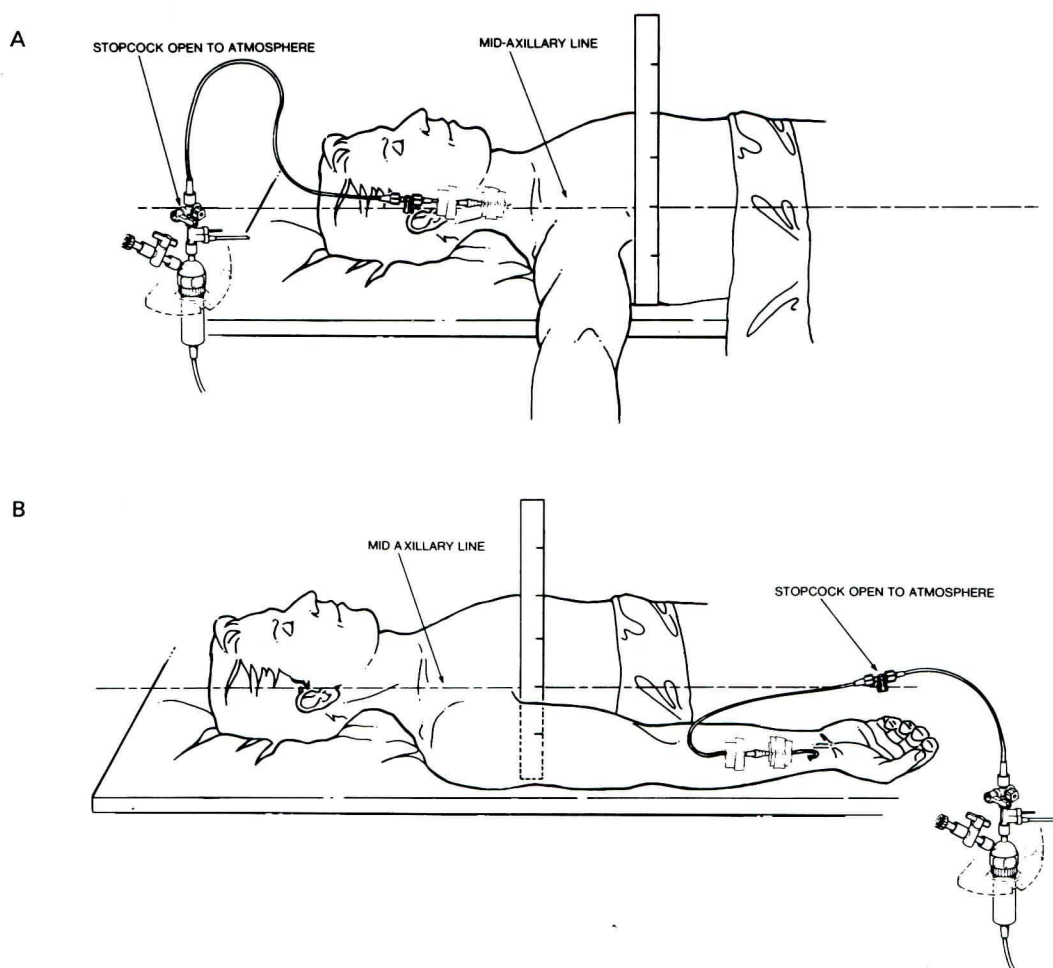


Fig. 2 — Two methods of zeroing a pressure transducer. Note the place at which the water-air interface occurs should always be at the mid-axillary line when zeroing. (A) The stopcock is placed near the transducer at the mid-axillary line. (B) The stopcock near the catheter is placed at the mid-axillary line. (Reproduced with kind permission from reference 2)

ured in the USA in 1989 were direct arterial pressure measurements. An average 70% of the intensive care patients in USA have direct arterial pressures measured. The growth rate of direct pressure measurement for the past five years has been about 5% annually. The USA conversion from reusable to disposable transducers was expected to reach 85–90% in 1989, with heart catheterization and labour and delivery (intrauterine) areas being the last to convert.

In Europe there are an estimated 2.5 million total pressures measured annually, with the 1989 conversion to disposable transducers estimated at 50 to 55%. Japan and Australia had an estimated 1.5 million pressure measurements. The conversion to disposable pressure transducers in Japan was only 25 to 30% in 1989. In Australia in 1989 the conversion to disposable transducers was 60 to 70%.

The sensitivity of the AAMI/ANSI interchangeable blood pressure transducers is fixed at $5.0 \mu\text{V} \cdot \text{V}^{-1} \cdot \text{mm Hg}^{-1}$ and calibrated by the manufacturer to be within 1%.¹⁰ This degree of accuracy is appropriate for clinical purposes. The accuracy and long term stability of the new disposable transducers

eliminates the need to perform 'sensitivity' calibrations of most monitoring systems.^{2,9}

Characterizing dynamic response

Catheter-tubing-transducer 'plumbing' systems used in the intensive care unit can be characterized as underdamped second-order dynamic systems with mechanical parameters: elasticity, mass, and friction.^{1,2,3,9,11-19} Second-order systems have a natural frequency (F_n) measured in Hz and a damping coefficient Zeta (Z) established primarily by the plumbing system.^{1,2,3,9,11}

Dynamic response characteristics of catheter-tubing-transducer systems are usually expressed by two interrelated techniques. The first method specifies a bandwidth (frequency) and require that the system's frequency response be 'flat' to within 5 or 10% up to a given frequency.^{1,16,17} With this method a specified number of harmonics (usually from 3 to 10 harmonics) of the heart rate ($60 \text{ beats min}^{-1} = 1 \text{ Hz}$) are required to be reproduced with minimum (5 or 10%) distortion (see Fig. 4). The second method specifies the natural frequency (F_n) and damping

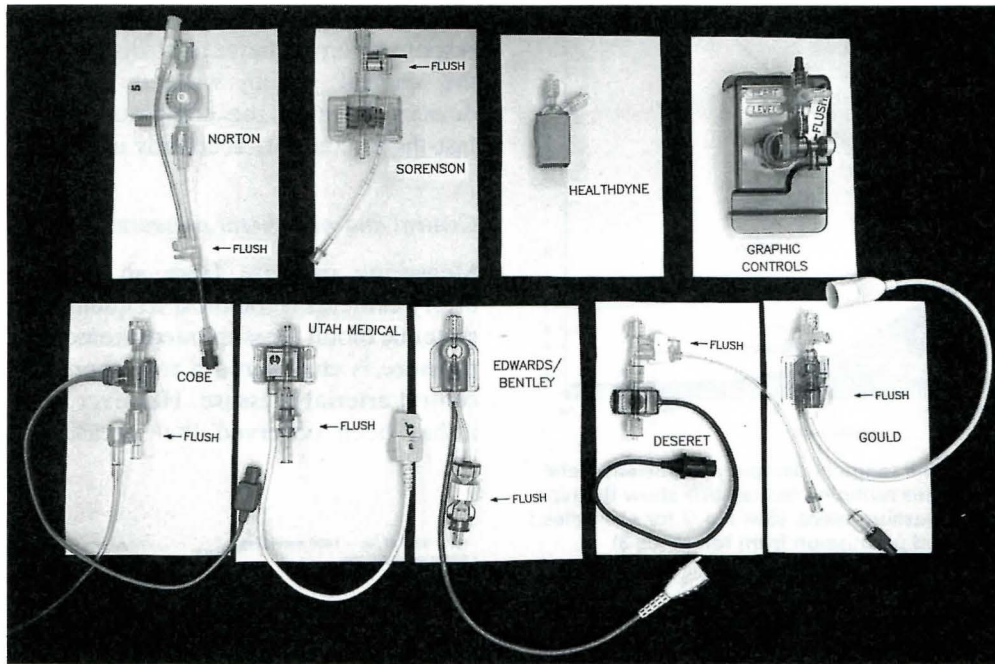


Fig. 3 — Disposable pressure transducers showing their small size (all have standard Luer fittings). Note that there are a variety of configurations and cable connections. Most have integral flush devices. The four transducers at the top are attached to their cables with internal connectors while the five transducers on the bottom connect with a 'pigtail' cable. The Cobe (lower left) has a Linden fitting while all others have Luer lock fittings. (Reproduced with kind permission from reference 9)

coefficient.³ A plot of natural frequency and damping coefficient shown in Figure 5 is used to classify the adequacy of dynamic response. If the characteristics of the plumbing system fall in the adequate or

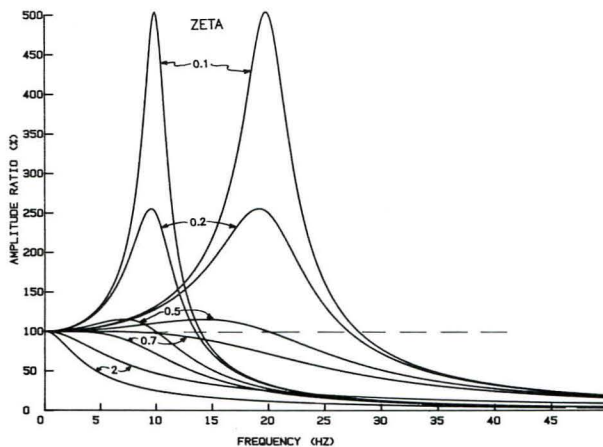


Fig. 4 — Family of frequency versus amplitude ratio plots for five different damping coefficients (Zeta) and two different natural frequencies, 10 and 20 Hz. A damping coefficient of 0.1 occurs if the system is very underdamped, while a damping coefficient of 2 occurs when a system is overdamped. The dotted line shows the ideal or 'flat' frequency versus amplitude response. Note that the response of the system with a 10 Hz natural frequency can be brought closer to the ideal 'flat' response if the damping coefficient is between 0.5 and 0.7. However, by increasing the natural frequency to 20 Hz, the range of damping coefficients can be widened still further and give nearly the same 'flat' frequency response. (Reproduced with kind permission from reference 7)

optimum area of the graph, the arterial pressure waveform will be adequately reproduced. (See Fig. 6 for examples of distortion.) If they fall in the remaining three areas, (damped, underdamped, or unacceptable) there will be waveform distortion. Catheter-tubing-transducer plumbing systems used for direct arterial pressure monitoring that are assembled under optimal conditions are usually underdamped and a few fall into the unacceptable area. In the clinical setting there are dramatic differences between each patient set-up, even with the same configuration of catheter, tubing and transducer. Therefore it is essential to test the dynamic response adequacy of each pressure monitoring system.^{2,3,11}

The dynamics response can be easily tested using the 'fast-flush' technique. The fast-flush is produced by opening the valve of the continuous flush device (for example by pulling and quickly releasing the pigtail on the flush device). The rapid closure of the flush valve generates a square wave, from which the natural frequency and damping coefficient of the plumbing system can be measured (see Fig. 6). Once the fast-flush test has been executed 2 or 3 times, the dynamic response characteristics (F_n and Zeta) can be quickly and easily determined. To determine F_n , the natural frequency, measure the interval between any two successive oscillations — For example see Figure 7-A. To determine the damping coefficient, any two successive peak amplitudes are measured and the amplitude ratio obtained (see Fig. 7-B). This ratio can then be converted to the damping coefficient by equation or graphically, using the scale on the right

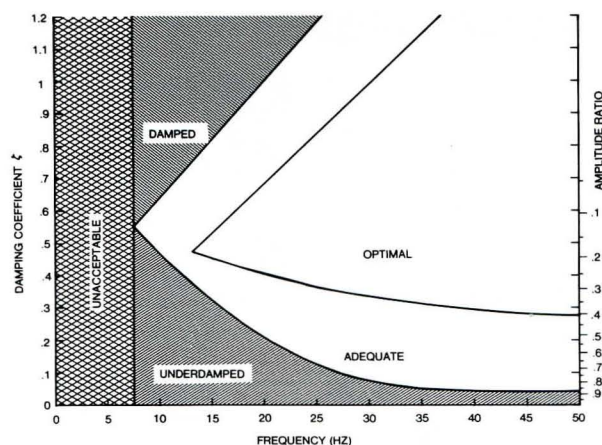


Fig. 5 — Plot shows the range of damping coefficient (Zeta) and natural frequencies outlining the regions show the type of distortion of the pressure wave. (See Fig. 7 for examples.) (Reproduced with kind permission from reference 3)

side of Figure 5. Once the natural frequency and damping coefficient have been determined the data can be plotted on Figure 5 to ascertain the adequacy of the dynamic response.

Several factors lead to poor dynamic responses: air bubbles in the system usually caused by poor initial plumbing system set-up; pressure tubing that is too long, too compliant, or with too small a diameter or pressure transducers that are overly compliant. The best way to enhance the system's dynamic response is to maximize its natural frequency.

Recently the dynamic characteristics of pressure monitoring systems have been modelled.¹¹ Figure 8 shows the effects of tubing length and the effect of different sized air bubbles in the transducer for three pressure monitoring systems. Air bubbles are the major cause of poor dynamic response in clinical pressure monitoring systems. From Figure 8 it is clear that 'air free' systems performed the best. As can be seen in Figure 8, systems with no air have the highest natural frequencies and the 'best' dynamic responses. Therefore, despite what is taught at some centers, adding air to the transducer to 'damp' the system is not a good idea. First, because the threat of arterial air embolism with its attendant consequences, and secondly because the insertion of the correct small volume of air, about 40 μ l for System A in Figure 8 is not practical. Also note in Figure 8 that systems with the shortest tubing have the highest natural frequency and thus the best dynamic response. Table 2 outlines steps that should be taken to test and optimize dynamic response.

Small bubbles in a monitoring system are often difficult to see and may be hidden in stopcocks or connections. Therefore, fast flush testing is essential to determine if a particular monitoring system setup is performing at its optimum. This testing is usually done by quickly estimating its natural frequency from the fast-flush test.

The fast-flush method is superior to other techniques for characterizing catheter-transducer systems

because it can be used to test the entire system response from catheter tip to display. It can be used in the clinical setting without attaching additional devices, because the continuous flush device with fast-flush capability is already in place.

Central and peripheral pressures differences

Measuring pressure from an intra-arterial radial artery catheter is the most frequently chosen site for systemic blood pressure measurement.²⁰ Usually this pressure is considered a true representation of the central arterial pressure. However, in recent studies it has been observed that occasionally there are

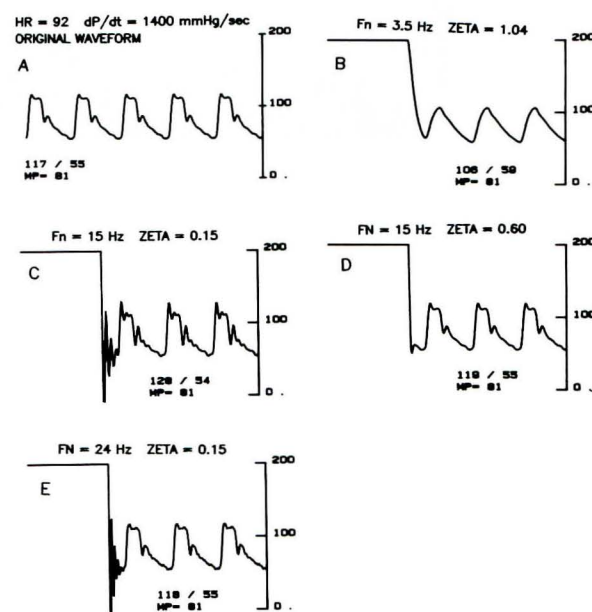


Fig. 6 — Arterial pressure waveforms recorded with different pressure monitoring systems. Patient heart rate is 92 beats per min with a maximum dp/dt of 1400 mm Hg.s⁻¹. **Panel A:** The original patient waveform as it might be recorded with a catheter tipped pressure transducer (high fidelity). The systolic pressure is 118 mm Hg, diastolic is 55 mm Hg, and mean pressure is 81 mm Hg. **Panel B:** The same patient's arterial pressure waveform recorded when an 'overdamped' plumbing system is used. Zeta is 1.04 and F_n is 3.5 Hz. Note the 'fast flush' signal (upper left) returns slowly to the patient waveform. Systolic pressure is underestimated at 106 mm Hg, diastolic is overestimated at 59 mm Hg, but mean pressure is unchanged at 81 mm Hg. **Panel C:** An 'underdamped' condition with a low damping coefficient of 0.15 and a natural frequency of 15 Hz. After the 'fast flush' the pressure waveform oscillates rapidly and returns to the original waveform shape quickly. Systolic pressure is overestimated at 128 mm Hg, diastolic is nearly the same as the original at 54 mm Hg, and the mean pressure is unchanged at 81 mm Hg. **Panel D:** Same as in Panel C, but now a damping device (such as the 'Accudynamic' or 'ROSE') is inserted and adjusted (see text). The waveform is optimally damped with a damping coefficient of 0.60 and a natural frequency of 15 Hz. **Panel E:** An 'underdamped' condition but with a high natural frequency of 24 Hz. Note the pressure waveform is only slightly distorted and the pressures are close to the true pressures. (Reproduced with kind permission from reference 11)

Table 2 — Recommendations for optimizing arterial pressure monitoring dynamic response in the clinical setting

1. Recommended frequency of dynamic response validation
 - A. At least once every 8h
 - B. After each 'opening' of the system such as for zeroing, blood drawing or changing of tubing
 - C. Whenever the pressure waveform appears to be 'damped' or otherwise distorted
2. Steps to optimizing dynamic response
 - A. Select monitoring 'kits' which are simple with a minimum amount of pressure tubing and non-compliant tubing, flush devices and transducers
 - B. Remove all air bubbles during setup especially near the transducer. Air bubbles in the side ports of 3 way stopcocks are invisible and can be troublesome. Eliminate them by fluid filling all the ports of the stopcock.
 - C. Minimize the potential for clot formation at the catheter tip by using a continuous flush system. Ascertain that there is not a clot in the catheter by 'fast flushing' and if necessary aspirate blood from the catheter
 - D. Eliminate kinks in the catheter or tubing
 - E. Eliminate long lengths (>60cm) or compliant interconnecting tubing
 - F. Use low volume displacement transducers and continuous flush devices
 - G. When all of the above steps have been taken and the system has a natural frequency greater than 7.5Hz then use of a damping adjustment device (Accudynamic^{2,3} or Rose¹⁵) is indicated

discrepancies between peripheral arteries such as the radial or dorsalis pedis pressures and those measured centrally (aorta).^{8,20,21} These situations have been seen most frequently following cardiac surgery.^{20,21} In every case the pressure in the peripheral artery is unexpectedly low. The measurement error can be

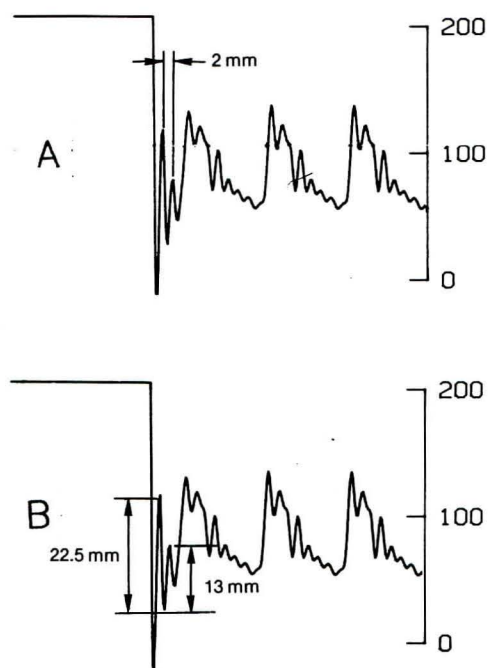


Fig. 7 — How to measure dynamic response parameters. **Panel A:** The natural frequency can be determined by using a strip recording to measure the period of one full oscillation resulting from the 'fast flush'. In the example shown, one full cycle is 2mm. Since the paper speed is 25mm sec⁻¹ the natural frequency is $F_n = 25\text{mm} \cdot \text{s}^{-1}$ per 2mm = 12.5 Hz. **Panel B:** Determination of damping coefficient (Zeta) requires the measurement of any two successive peak amplitudes as shown. Then the ratio of the two amplitudes is taken. Here the amplitude ratio = $13/22.5 = 0.58$. Using the amplitude ratio scale on right hand side of Figure 5 we find that the damping coefficient is 0.17. (Reproduced with kind permission from reference 9)

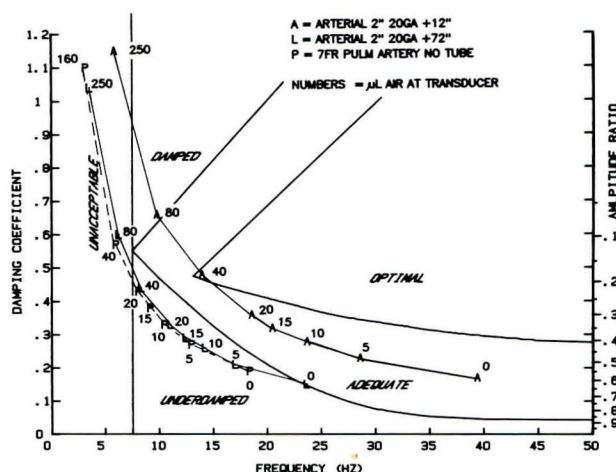


Fig. 8 — Plot of F_n versus Zeta (damping coefficient) for two arterial pressure monitoring systems and one pulmonary artery system, showing the effect of inserting small air bubbles at the transducer dome. The volume of the air bubbles in microlitres are shown near the marks on the curves. The curves were generated with the use of computer modeling. Results are presented for a short radial arterial catheter (Deseret 2 inch catheter) with 12 inches of pressure tubing (A upper curve). The same catheter with 72 inches of pressure tubing (L), and pulmonary artery catheter (P). The best operating conditions are always obtained with no air in the system — the condition that gives the highest natural frequency. It is clear from clinical evaluations that many pressure monitoring systems have large amounts of air and give unacceptable dynamic response. (Reproduced with kind permission from reference 11)

corrected by inserting a femoral arterial catheter²⁰ or a catheter whose tip is advanced to or near the aorta.⁸ The aortic-peripheral artery gradient is usually transient and in most instances corrected by volume loading.

Processing and display errors

Extracting data from the direct arterial pressure waveforms typically provides reliable measures of systolic, diastolic, and mean pressure, and heart rate. However, bedside monitors with their microprocessor sophistication have done little to recognize and reject several artifactual conditions.⁹ For example,

when zeroing the transducer-amplifier system, most commercially available bedside monitors display and record 'zero' pressure. By recording these artifactual pressures, alarms are activated, data transmitted to recording systems and internal trend plots record erroneous data. When fast flushing these systems to verify dynamic response characteristics, monitors display, transmit, and record erroneous pressures. When drawing blood from the patient with the stopcock near the patient turned off, most monitors display and record erroneous pressures from the flush bag (usually near 300 mm Hg) with no indication that a blood sample withdrawal was occurring. In the next few years monitor designers must correct these design flaws.⁹

Conclusions

Clinical use of direct blood pressure monitoring has been in everyday use for over 25 years. During that time a procedure that was difficult and required special medical and engineering skills has now been simplified by new techniques and devices that allow data collection with fewer errors. Nonetheless, the clinical user must always be vigilant about data derived from bedside monitors. Only after careful validation of the performance of the monitors and the systems discussed here should the blood pressure results, that are so effortlessly generated, be used to make clinical decisions.

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